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EIC Detector R&D Progress Report

Project ID: eRD17

Project Name: BeAGLE: A Tool to Refine Detector Requirements for eA Collisions

Period Reported: from July 2019 to December 2019

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Abstract

As part of the EIC R&D program, the BeAGLE (Benchmark eA Generator for LEptoproduction) model code for simulating e+A collisions has evolved into a key element in the current efforts to refine the detector and interaction region design for both eRHIC and JLEIC, particularly in the forward region in the ion-going direction. As discussed in the July 2019 committee report, the project is starting to transition to a stage where maintenance and support become increasingly important, but key aspects of code development are still underway. Because the conclusions from e+A studies using BeAGLE may drive the forward detector/IR designs and possible tradeoffs, it is imperative that we use the best possible models and tune BeAGLE using our best information, as soon as possible.

To that end, we will focus this report on articulating the current priorities and how we are balancing them. Important issues in support/maintenance include: fixing known issues in 4-momentum conservation, releasing a solid tagged “production” version of BeAGLE, and submitting a publication on BeAGLE. The two extensions to BeAGLE capabilities that we are already pursuing include: implementing the correct light-cone kinematic behavior for e+D and adding RAPGAP as an option in addition to PYTHIA to better describe elastic or diffractive hard e+N scatters. Further possible extensions include implementing SRCs (Short-Range Correlations) directly in BeAGLE and allowing for nonzero crossing angle as well as event-to-event variations in beam 3-momentum. We continue to work on validating BeAGLE’s physics model (DIS + diffraction + nuclear effects) by tuning to the relevant E665 data.

We also discuss briefly the situation with external funding.

Past

What was planned for this period?

The most important task was supporting various studies using BeAGLE to help refine the IR/Forward Detector requirements for e+A.

The highest priority technical items listed in the July 2019 proposal talk (see p. 17)[1] were:

- Getting reasonable agreement between BeAGLE and the E665 kinematic distributions, in particular the Q^2 distribution which contains significant variation due to trigger inefficiency at low Q^2 .
- Finishing the implementation of RAPGAP into BeAGLE.
- Finishing the extension of RAPGAP to include e+n collisions as well as e+p.
- Implementing the correct light-cone kinematic behavior for e+D collisions.

We also planned to prepare a publication using BeAGLE which would be associated with a specific tagged version.

What was achieved?

The ongoing, most important, task of supporting BeAGLE studies for the EIC was successful. The most notable example of the fruits of this effort was the fact that there were six talks reporting on BeAGLE-based studies at the “Joint CFNS & RBRC Workshop on Physics and Detector Requirements at Zero-Degree of Colliders” held on 24-26 September 2019 [2]. Three of these were by eRD17 participants: Baker, Chang & Tu, while three were by users: Florian Hauenstein (ODU/JLAB), Pawel Nadel-Turonski (SBU) & Barak Schmookler (SBU). Various talks at other meetings also occurred during this time period, including those by Zhoudunming Tu(BNL), Yulia Furletova (JLAB) and Vasiliy Morozov (JLAB), among others.

Four figures from Wan Chang can serve to illustrate a subset of the ongoing studies being done with BeAGLE. Figure 1 is a simulation of e + Pb collisions at two beam energies, showing the angle vs. momentum distribution for evaporation neutrons and protons. Figure 2 and 3 show that cuts on ZDC (Zero Degree Calorimeter) energy, which is basically proportional to the number of evaporation neutrons, can be used to control the geometry of e + A collisions. Figure 2 shows that a high E_{ZDC} “central” sample corresponds to a smaller impact parameter b and a larger distance parameter d compared to a low E_{ZDC} “peripheral” sample. The distance parameter d is defined as the amount of nuclear material (e.g. in nucleons/fm²) in the nucleus downstream of the first struck nucleon normalized by the density in the bulk of a Pb nucleus (in nucleons/fm³). The ratio d is therefore in units of distance (fm) and corresponds to the equivalent distance in full-density nuclear material traversed by the reaction products. Figure 3 shows that it is meaningful to make a relatively tight “central” cut, such as 1% instead of 5% or 10%, since the average value of the d

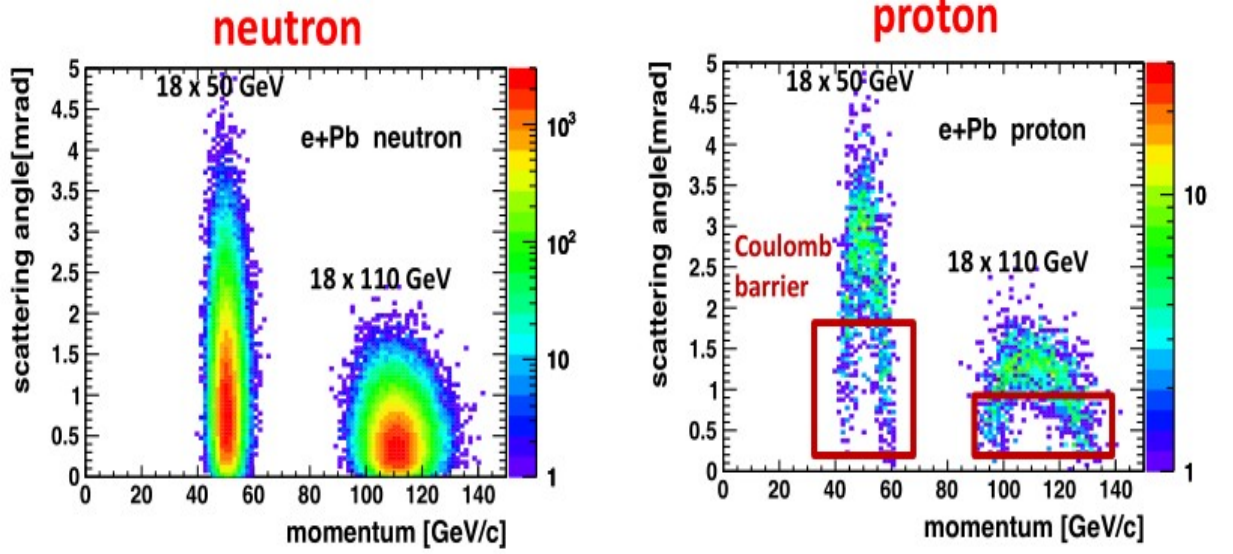


Figure 1. BeAGLE simulation of the momentum and scattering angle distributions for evaporation nucleons in e+Pb collisions.

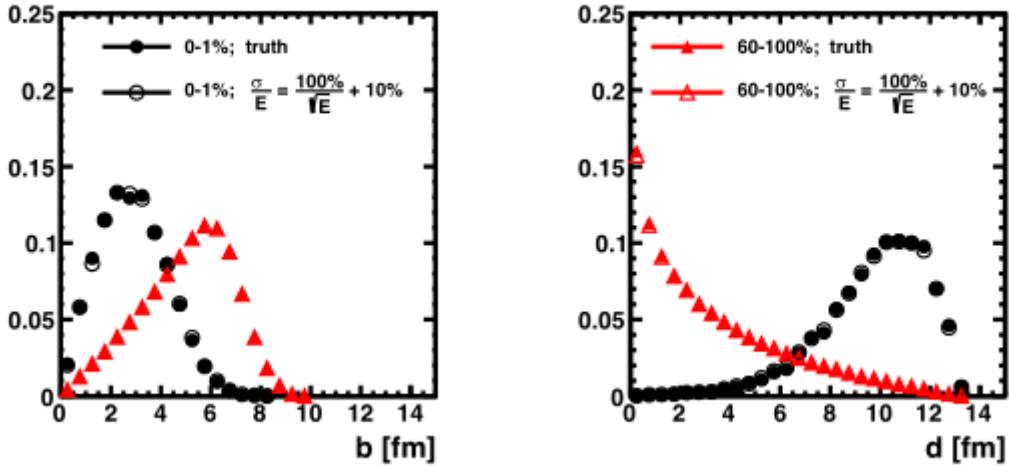


Figure 2. A comparison of the geometric parameters 1% most “central” and 40% most “peripheral” e+A collisions according to ZDC (Zero Degree Calorimeter) energy, where 0-1% is the 1% highest ZDC energy and 60-100% is the 40% lowest ZDC energy. The impact parameter is b and d is the amount of nuclear material traversed after the first collision normalized by a typical nuclear density. Closed symbols correspond to a perfect ZDC while the open symbols correspond to a rather low quality ZDC.

parameter continues to improve. Figures 2 and 3 also illustrate one important difference between e+A and A+A. Central A+A collisions correspond to small values of E_{ZDC} with very few spectator neutrons surviving the collision unscathed, while central e+A collisions correspond to high values of E_{ZDC} with a large number of evaporation and other neutrons. For central A+A collisions, we are used to a substantial effect of detector energy resolution. For central e+A collisions, however, dozens of neutrons from evaporation or intranuclear cascading hit the ZDC and each of them showers independently in the detector, leading to a $1/\sqrt{N_n}$ improvement in

the energy resolution. In particular, Figures 2-3 show the (lack of) impact of the calorimeter resolution on the geometry measurement. Open symbols correspond to a rather poor resolution for individual showers of $\sigma_E/E = 10\% + 100\%/\sqrt{E/\text{GeV}}$ and the results are nearly indistinguishable from a perfect calorimeter with $\sigma_E/E=0\%$. It should be noted that there are other measurements where the ZDC energy resolution is more important, but we were surprised by how insensitive the geometry cuts are to calorimeter resolution. It had been an open question and occasional criticism of previous studies using an ideal calorimeter. Those concerns can clearly be put to rest.

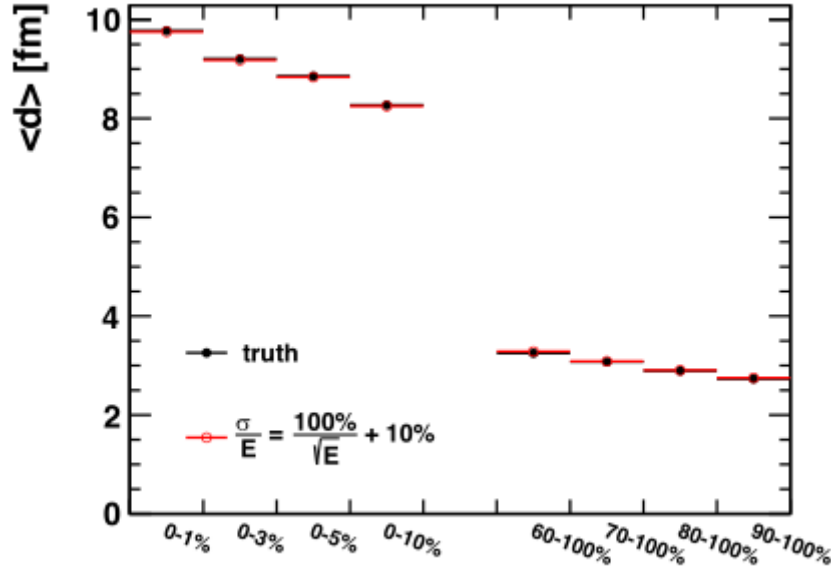


Figure 3. The average value of the geometry parameter “d” for various choices of centrality bins. Black closed circles correspond to a perfect calorimeter while open red circles correspond to a calorimeter with $\sigma(E)/E = 100\%/\sqrt{E/\text{GeV}} + 10\%$.

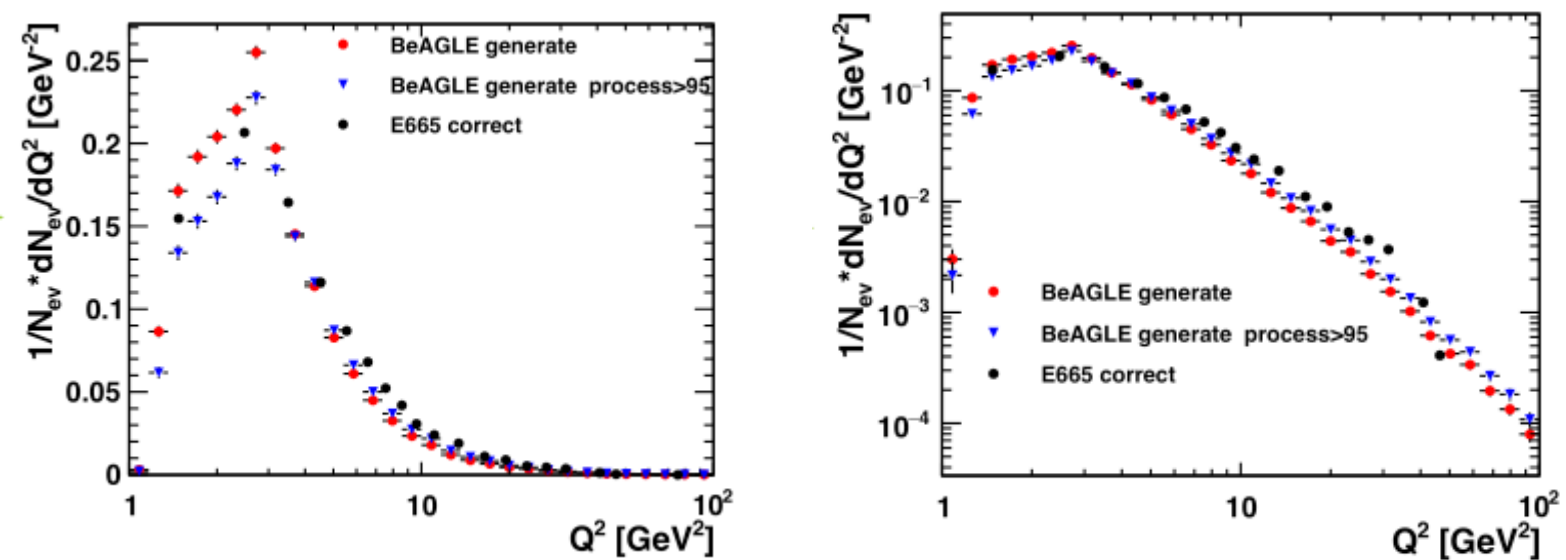


Figure 4. E665 corrected Q^2 distributions for $\mu + \text{Xe}$ data compared to BeAGLE. E665 corrected data adapted from Figure 2 of Ref.[3].

The E665 Collaboration presented their kinematic distributions, including the Q^2 distribution in an unusual way [3]. Rather than just presenting the data corrected for trigger and detector acceptance, the uncorrected data were shown as data points and a curve showing the acceptance factor was included on the same plot. After using the curve to correct the E665 data, we can then compare the corrected data to BeAGLE and this yields satisfactory results, as seen in Figure 4.

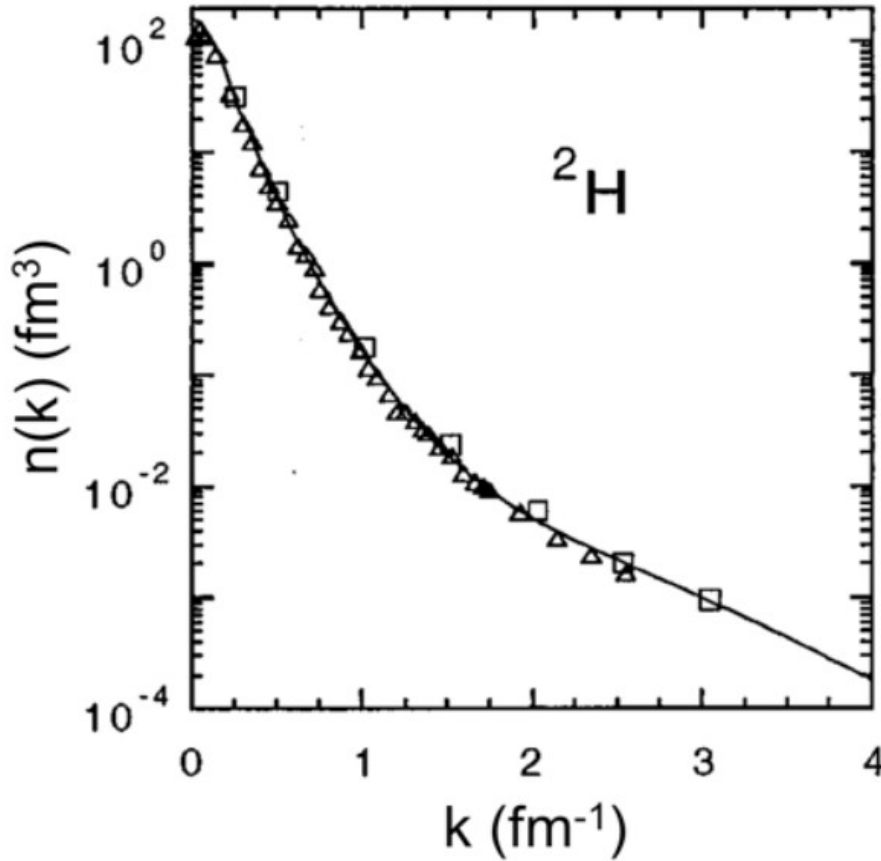


Figure 5. A model for the nucleon momentum distribution $n(k) \equiv dN/dk / (k^2)$ within the deuteron, where k is reported in units of $(\text{fm}^{-1}) \approx 197 \text{ MeV}$ (natural units with $\hbar=1$). As discussed in the text and Ref. [4], k is now to be interpreted as being in the incoming $n+p$ rest frame, not the deuteron rest frame. Figure taken from Ref. [5,6].

The correct handling of $e+D$ collisions is a relatively new project which we took on and it has not really been done before in a general purpose Monte Carlo, only in very specific applications[7]. As discussed in previous reports, handling the binding energy of the deuteron is not straightforward or obvious: either the nucleons must be treated as off-mass-shell (difficult in Pythia) or you have to allow a specific type of 4-momentum non-conservation for the internal vertices, while conserving the 4-momentum for all external lines, an approach called the light-cone formulation[4]. At this point, following extensive discussion between Baker and Tu and theorists Christian Weiss (JLAB) and Mark Strikman (PennState), the necessary approach is

finally clear and should be relatively easy to implement. The key point is to describe the distribution of the spectator nucleon using a “spectral function” and that a reasonable approximation is to take the $n(k)$ distribution[5,6] (see Figure 5) which we already implemented and interpret the “ k ” parameter slightly differently. In the light-cone formulation, the k is the 3-momentum of the spectator nucleon in the incoming $n+p$ rest frame, NOT in the deuteron rest frame, as we originally implemented it. Because of the 4-momentum non-conservation previously mentioned, these are not quite the same.

In any case, now that it is understood, this implementation of $e+D$ will be straightforward. Furthermore, it is easy to add optional alternatives in the future if better models for the spectral function are later provided by theorists. In particular, the solution presented above is known to be just an approximation which works best at small or modest values of k/M_N .

What was not achieved, why not, and what will be done to correct?

The technical tasks are progressing well, although it is possible that some will slip by a month or two. At the moment, nothing has fallen behind schedule, although our plans for January – completing RAPGAP installation and releasing a paper – may be a little tight. The RAPGAP implementation is in the process of being debugged. There has been no fundamental problem with this project, it just keeps getting bumped for other, more urgent, issues. We expect to make a push on this to complete it by the end of January, our latest target. The extension to $e+n$ should be relatively straightforward, but also needs to be done, either by Baker or by Hannes Jung.

Future

What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

We will continue to prioritize the most urgent tasks as we proceed. In addition to the tasks above, lower priority tasks remain on the agenda with a complete list in Table 1.

Feature added or error corrected	07/2019	12/2019	Priority
1-8,10,13-17,20-22,24. Completed BeAGLE tasks.	YES	YES	
9. Shadowing coherence length	NO	NO	Low
11a. Effective σ_{dipole} for J/ψ averaged over x & Q^2	YES	YES	
11b. Effective σ_{dipole} for ϕ averaged over x & Q^2	YES	YES	
11c. Eff. $\sigma_{\text{dipole}}(x, Q^2)$ for $V=\psi, \phi, \rho, \omega$ from Sartre (ePb)	NO	NO	Low
11d. Use correct $R_{\text{diff}}^{(A=208)}(x, Q^2)$ for V from Sartre	NO	NO	Low
11e. Improved σ_{dipole} for V , if necessary	NO	NO	Low
12a. Understand E665 Event Trigger (& Q^2 dist.)	NO	YES	
12b-?. Tune to E665 μA Streamer Chamber data	NO	NO	Medium
18. Tune the t distribution for multiple scattering.	NO	NO	Low
19a. Release α version BeAGLE/RAPGAP	YES	YES	
19b. Release β version BeAGLE/RAPGAP	YES	YES	
19c. Fix charge non-conservation bug (DPMJET-F)	YES	YES	
19d. Fix lost energy bug (DPMJET-F)	YES	YES	
19e. Fix excess energy bug (DPMJET-F?)	YES	YES	
19f. Release tested version BeAGLE/RAPGAP	NO	NO	High
19g. Extend RAPGAP to include $e+n$ (w/ H. Jung)	NO	NO	High
23a. Put $e+D$ on mass-shell (ad-hoc)	YES	YES	
23b. Put $e+D$ on mass-shell, light-cone prescription	NO	NO	High
25. Fix smaller and/or rarer 4-momentum bugs	NO	NO	Medium

Table 1. Task list with a priority level for completing remaining tasks.

The high priority items have been discussed above. Item 12a has been completed. Items 19f-g (RAPGAP) are due in late January, with item 23b ($e+D$) to follow shortly thereafter.

The medium priority items are line 12b and the new line 25. Line 12b-? refers to comparing BeAGLE to the E665 Streamer Chamber data once BeAGLE handling of diffraction has been improved. This is really one of the main thrusts of the entire project, but it is medium priority since it is waiting for other items such as 19 and 25. Line 25 refers to remaining errors in 4-momentum conservation that are typically of the scale of about 100 MeV (small fraction of the few TeV of energy present in the ion rest frame) or the small fraction of events ($<0.01\%$ for EIC energies) with 1 GeV level errors.

Finally, we have the low priority tasks which are only really necessary if they are needed in order to match the data.

Item 9, “shadowing coherence length” has been repeatedly postponed because it is not very important for many of the studies so far which have focused on small x ($x < 0.002$) or on the valence region. E665 data, however, includes a substantial amount of data in the transition region $0.01 < x < 0.1$ where the coherence length could be important.

Items 11c-d are further improvements to the diffractive dipole (rescattering) cross-section and the overall eA/eN diffractive cross-section ratio. These are also important for the comparison of E665 data with RAPGAP-enabled BeAGLE. Item 11c refers to a plan to use the Sartre results to infer the correct dipole cross-section for multiple scattering for each vector meson as a function of Q^2 and x rather than just matching the value averaged over Q^2 and x . Item 11d refers to making sure that the overall diffractive cross-section ratio between ePb and eN matches that of Sartre. Finally, item 11e recognizes that a better formalism may be needed to relate Sartre $\sigma(eA)/\sigma(eN)$ behavior to the rescattering probability in BeAGLE, especially for the ϕ, ρ, ω mesons where the suppression due to gluon saturation is strong and therefore the inferred rescattering cross-section is large.

Line 18 refers to a small improvements to the BeAGLE model for the effect of shadowing. Currently, the scale of the soft multiple scattering is given by the intrinsic k_T of the parton in the nucleon. For the diffraction case, this scale should be given by the t distribution of the elastic component of incoherent diffraction.

Further possible extensions to BeAGLE have been discussed. These include implementing SRCs (Short-Range Correlations) directly in BeAGLE and allowing for nonzero crossing angle as well as event-to-event variations in beam 3-momentum. As discussed below, there is a JLAB initiative to apply BeAGLE simulations to JLAB and JLAB12 fixed target projects and the SRC extension may be more urgent for that project, as may be the “shadowing coherence length” discussed above.

What are critical issues?

We do not foresee any major difficulties with the implementation of the BeAGLE upgrades. The main open-ended issue is how well BeAGLE will match the E665 data when the upgrades are finished and how much tuning will be needed if there are significant discrepancies.

As noted by the committee in July, the EIC project is maturing and the nature of EIC R&D is changing. Support for BeAGLE maintenance and further development will still be needed in the out years: FY2021 and beyond.

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.

Baker is the only directly funded person on the project, working one-quarter time (0.25 FTE) on average. Wan Chang’s travel support at BNL will be partially

supported by the project. She is a student working roughly 50% on EIC R&D who is actively supervised by Elke Aschenauer. Aschenauer and Tu have been actively involved in the project in the past reporting period, while Lee continues to provide valuable advice.

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

Brookhaven National Laboratory Physics Department funding supported the salary of Aschenauer, Lee and Tu and part of the travel support for Chang. Similarly, China University of Geosciences (Wuhan) supports Liang Zheng's salary and China Central Normal University supports Wan Chang's salary and tuition.

Baker, Tu and Zheng participated in a JLAB LDRD project in FY2019: "Tagged Short-Range Correlations For Medium To Heavy Ions at JLEIC", which included an upgrade of the BeAGLE nuclear model to allow the possibility for quasi-deuterons as well as independent neutrons and protons inside of the nucleus. Collaborators, in addition to Baker, Tu and Zheng included: Abhay Deshpande(SBU), Or Hen (MIT), Florian Hauenstein(ODU), Douglas Higinbotham (JLAB – PI), Charles Hyde (ODU), Vasilij Morozov (JLAB), Pawel Nadel-Turonski (SBU), and Barak Schmookler (SBU). Unfortunately, this project was not renewed for FY2020 – as all EIC-specific projects were deemed too near term for further LDRD support by JLAB. Separate funding sources at JLAB and MIT have been identified and tapped to pursue this effort at some level in FY2020. The focus will of this effort will now be on fixed target energies (JLAB and JLAB12), but any improvements to BeAGLE should still be useful for EIC studies as well.

Publications

Please provide a list of publications coming out of the R&D effort.

One paper is under preparation, and more are envisioned.

Conclusion

As part of the EIC R&D program, the BeAGLE (Benchmark eA Generator for LEptoproduction) model code for simulating e+A collisions has evolved into a key element in the current efforts to refine the detector and interaction region design for both eRHIC and JLEIC, particularly in the forward region in the ion-going direction. The eRD17 project continues to engage in relevant studies as well as supporting the efforts of various users. Furthermore, we continue to develop the code as planned as well as reacting to well-motivated user requests for improvements. Because the conclusions from e+A studies using BeAGLE may drive the forward detector/IR

designs and possible tradeoffs, it is imperative that we use the best possible models and tune BeAGLE using our best information, as soon as possible.

Bibliography

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